Load Management for Seasonal Heat Storage Applications based on Sorption Storage Technology

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Abstract

Based on the current energetic scenario worldwide, it is possible to observe that the necessity of storing the large supply of solar energy available during summer and using it during winter, when the accessible quantity of energy is not so big, is greater than ever. Therefore, seasonal storage systems with both, high energy density and low thermal losses, are needed. Energy storage systems based on thermochemical materials like zeolite, such as the one described in this study, are the most adequate option to achieve this goal, due to their potential to fulfill both requirements earlier described. In the scope of this study a load management strategy was developed for a sorption storage system in which the material should be dried during summer and used during winter, working this way as a seasonal heat storage. The first results show the creation of the two storage containers, dryer and divider and how the weather data used can influence the system.

Keywords: Sorption, Storage, Thermochemical materials, Zeolite

1. Introduction

A broad deployment of energy storage technologies for an increased share of renewable energy is motivated by global climate action and the ambition of CO_2 reduction (Daborer-Prado, et al. 2020). Industrial waste heat, building integrated renewable energy generation, surplus heat but also electricity of power plants and grids which show fluctuation and volatile behavior, are reaching dimensions worth storing energy in larger quantities. Depending on the involved temperature levels the potential energy savings can be considerable, the highest being for the low temperatures ranging from 50 to 150°C.

Taking that into account, thermal energy storages (TES) are believed to be appropriate candidates to play an important role in the future thermal management system. They can be defined as the temporary storage of thermal energy at high or low temperatures for diverse periods of time, this way preventing the loss of thermal energy. TES systems have an important capacity of making the use of thermal equipment more effective and represent a relevant way of decreasing the mismatch between thermo-availability and demand, providing also an environmental and economic benefit by reducing the need for burning fuels (N. Daborer-Prado 2019).

The TES systems can be classified depending on the temperature range, primary heat source, storage material, storage duration and field of application. Regarding the physical storage principle, it can be categorized in the following forms (Haider und Werner 2013):

- Sensible heat storage
- Latent heat storage
- Thermochemical heat storage

Figure 1 presents the classification of thermal energy storage materials according to the state in which the TES reveal itself.

doi:10.18086/eurosun.2022.13.05 Available at http://proceedings.ises.org

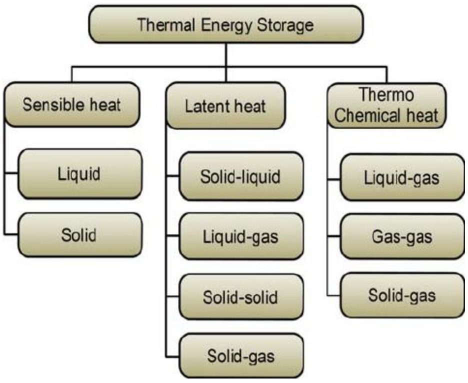

Figure 1: Classification of thermal energy storage technology based on the criterion of the state of the energy storage material. Source: *(Hauer, et al. 2020)*

The ability of thermochemical materials (TCM) to store energy long-term with practically no losses during the conservation phase makes them promising candidates for seasonal storage applications (Hauer, et al. 2020), (Issayan und Zettl 2021). High energy densities using the zeolite-water couple have been demonstrated for some applications, exceeding those of water storage by a factor of 2-3 (Issayan und Zettl 2022), (Issayan, Zettl und Somitsch 2021). Zeolites are crystalline aluminosilicates of alkali or alkali earth elements, such as sodium, potassium, and calcium. When dehydrated zeolite gets in contact with water vapor, the water molecules enter the internal crystal lattice and causes an adsorption reaction that leads to the release of heat. The reverse process happens when zeolite is heated to more than 100°C (desorption), when the water molecules are released from the sorption material. The adsorption/desorption process in zeolites can be repeated multiple times with practically no deterioration of the material (Socaciu 2012).

The physical principle of the sorption cycle is demonstrated in Figure 2: Gaseous water molecules can accumulate on the surface of the solid, releasing heat from binding and condensation (adsorption), when the temperature increases or the partial pressure decreases, the substances separate again (desorption).

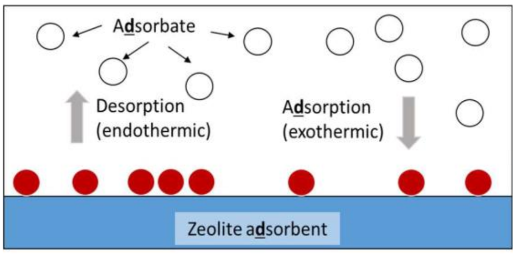

Figure 2: Adsorption principle - water vapor is attracted to the surface of another (solid) matter and heat is released. Meanwhile, the reversed process is the desorption

There are several process solutions for sorption technology, open and closed systems, as well as moving-bed and fixed-bed reactions, which have specific advantages (Hauer, 2020), (Krese, et al. 2018):

- Open: the reactor containing the sorbent material is at atmospheric pressure and throughout the charging process a dry air stream is conducted to it. One of its advantages is that it does not require the use of condensers, evaporators, or working fluid storage reservoirs, having this way a simpler and cheaper design when compared to closed systems.
- Closed: the reactor is under vacuum condition and requires one or more condensers and evaporators. The entire system is sealed from the surroundings and only water can flow through the conduct passage that connects the reactor to the evaporator/condenser. The reactor contains the reactive sorbent, and the condenser/evaporator is where the liquid water is collected.

The open moving bed reactions in particular offer the possibility of being able to freely dimension energy content and performance (B. Zettl 2020), (B. Zettl 2022). Air is used here as a moisture and heat carrier to dry the material in portions during the loading cycle. As this is a seasonal storage tank, the loading process is carried out in the summer during periods of high solar gains. However, storage loading requires a targeted strategy to take site-specific and environmental factors into account. Forecast models and learning algorithms are necessary for the energy management of the load. In contrast to large (fixed bed) storage vessels, the zeolite of a moved bed system is heated up in small batches for shorter time periods for minimizing heat losses. The batch-wise treatment brings up the risk for under/over-dehydration of the batches that could sum up to a severe reduction of efficiency during the summer season. Several model predictive control schemes have been proposed to exploit the diversity of the available energy sources. (Darivianakis, et al. 2017) investigated a data driven stochastic optimization approach for the seasonal energy management. It uses available historical data to build bounds that present a high probability of holding an optimal charging trajectory of the seasonal storage and generates a piece-wise approximation of the value function of the energy stored in the seasonal storage at each time step. (Parisio, Vecchio und Vaccaro 2012), on the other hand, presented optimization approaches for the energy management in energy hubs.

In this study, a model of the charging management and optimization algorithms is presented in order to be able to achieve the goal of the most complete possible regeneration of the TCM at the end of the charging cycle, and to display the changes of the dehydration result due to deviations of weather profiles from the representative average.

2. Methods and methodology

2.1. Application principle

The thermochemical storage with zeolite consists of two containers for dry and moist material as well as a dryer and an adsorption reactor, which was previously described (Zettl, 2020). During the heating period, one container with dehydrated zeolite is emptied in portions to provide heat for heating and hot water and stored in the humid material container. In central European climate approx.100 portions of the storage material should be available for 100 heating days.

In summer, the storage material is regenerated by renewable energy that has a daily cycle. The material is removed from the container, then heated, and dehumidified in the dryer. The material is then stored in the second container or transported back to the wet container if it has not dried sufficiently. Depending on the drying result, there is an inhomogeneous material moisture content in the two containers, which, however, levels out again after several days of storage. This leveling process and the desorption processes in the dryer are to be simulated. Furthermore, a control strategy should be achieved in order to decide whether the material is transported back into the moist or into the dry container.

The daily cycle is assumed to consists of 10 consecutive steps with one hour duration each during the daytime, at night local moisture differences tend to equalize in the container. After every hour, one-tenth of the daily portion is transported to the dryer, where it is desorbed and then moved, based on the decision of the material switch to the target container. After approximately 150 days of sufficient regenerative energy, all 100 daily portions of the material have dried. A seasonal storage should complete its loading cycle by the end of summer therefore weather profiles from 1st of May until 30th of September are considered for simulation runs

For simulation purpose, the model of the container is to be divided into 1000 cells (batches of hourly treatment). All cells are arranged in serial (first in/first out), in a use case each cell would correspond to a material quantity of approx. 5-10 kg of zeolite. The material in each cell has a dimensionless homogeneous moisture content (0 to 1) in this study. The material temperature and thermal losses are ignored so far, the dehydration is simply related to the energy gain from the solar generator. Figure 3 is a graphical representation of how the system works.

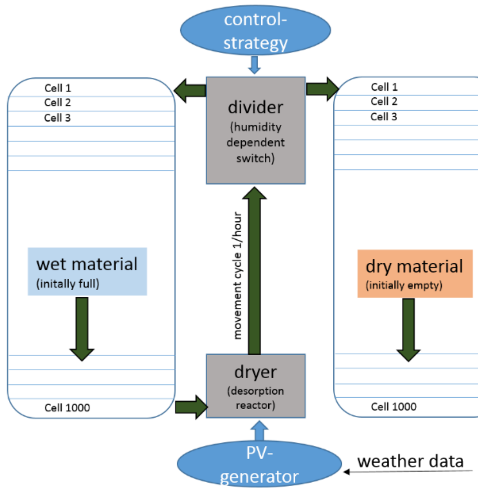

Figure 3: Principle of the material desorption cycle. Desorption is obtained by drying the TCM and transportation to one of the containers depending on the management strategy of the divider component

3. Results and discussion

3.1. Model implementation

The first step of this work was to create a mathematical model for the container. The moisture equalization process between the cells was represented as a conduction process, meaning that the higher the moisture difference between two neighboring cells, the more moisture is exchanged per unit of time, but no thermal process was considered.

In the simulation model, a characteristic constant that controls the conduction was chosen. This constant should work in a way that the leveling takes place up to a maximum difference of 1% (from one cell to its neighbors) within 24 or 48 hours. In practice, the greater the constant, the faster the process will take place. For clarity, Figure 4 and Figure 5 present the first results obtained by the creation of a mathematical model for the container and its behavior when an arbitrary change in humidity in certain cells takes place.

In both results, the first 10 cells had their humidity from 100% to 80% changed. Although the whole container presents 1000 cells, to better observe the outcomes, just the first 50 cells are shown in the graphs. The difference between the results lies in the humidity leveling factor used. In Figure 4, the factor was 0.1, and in Figure 5, it was 0.4. It is possible to observe that the higher the factor, the faster the humidity inside the container equalizes.

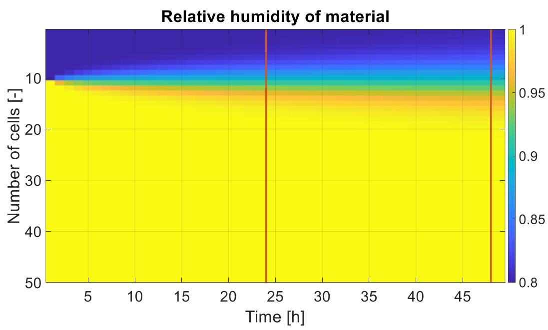

Figure 4: Relative Humidity in container with humidity leveling factor 0.2, leveling after 48 h

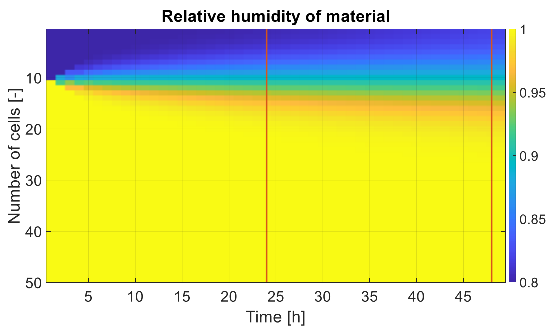

Figure 5: Relative Humidity in container with humidity leveling factor, leveling after 24h

As previously mentioned, the next step of the study was to add a second container to the model, as well as a material divider and a dryer. The second container was created based on the code of the first, with the difference that, the second container is initially empty and must be filled with dried material along the summer in a timeframe of 150 days. To avoid ambiguity, the first and second container will be named Drying and Store, respectively.

Dryer

The dehydration process is described in principle by a zeolite adsorption/desorption model already published. This model describes the increase or reduction of the material water content based on the applied process temperature and vapor pressure in the reactor (dryer). For simplification, the storage system including the dryer is operated on a dimensionless humidity factor (0 to 1) so far, and a nonlinear humidity reduction factor of the dryer (based on the input energy or solar irradiance).
For simulation a weather data was included in the model to simulate how the drying process will work based on the different solar irradiation values during the examined timeframe. Aiming to test the model with different types of data, three different files were extracted from the Carnot library (Juelich 2020):

- Weather of an average year
- Weather of an extreme summer
- Weather of an extreme cold summer

Depending on the solar irradiation input, the drying effect simulated in the dryer can be higher or lower. This effect is controlled by a lookup table created in the model. Essentially, the highest irradiance value will generate a drying effect of the material up to 80% The lowest irradiance measurement, usually zero, correspondingly represents a drying effect of zero as well. The irradiation values in between represent a drying effect ranging from 5% to 75% in a non-linear manner. During the night, the only process happening in the containers is the equalization of the moisture in the material stored.

Divider

Regarding the mathematical model of the divider, an operation principle was developed, in order to determine which action (transportation to one of the two containers) should take place after the material went through the dryer. During phase one (day 1 to 50) all material going through the drying process should be transported back to the Drying container in order to be dried once more, unless it has reached the “Low threshold”. In this case the material is then transported to the Store container. During the second phase (day 51 to 150), a variable threshold is set to define the minimum humidity in order to reach complete filling of the Store container. For that a “High threshold“ is set that represents the highest allowed humidity in the container for the “worst case” weather situation. Based on that, if the material’s humidity is higher than the threshold, it is transported back to the Drying container to be dried again and respectively, if the humidity is equal or lower the threshold, the material will be transported to the Store container The values for the "High threshold” and the “Low threshold” where obtained using the extreme (hot and cold) weather data set like explained in the next section.

3.2. Results

For the first results, the following input parameters were considered:

- Humidity leveling factor (hf): 0.4
- Divider threshold: 50%
- Number of cells in container: 1000
- Time: 150 days
- Average summer weather data

Figure 6 and Figure 7 present how the humidity inside of the containers change with time. The color bar on the right side displays the humidity of each cell, the dark blue cells have a material humidity between 0 and 30%, the light blue and green present a humidity between 40 and 60%, while the yellow cells have a humidity between 80 and 100%. It is possible to observe that in the drying container all the cells start the process with 100% humidity. As it was mentioned before, the material on the bottom of the container is removed to be dried and then it is placed back on the top of the container with a lower humidity, therefore as it can be seen, the humidity starts to change from the top to the bottom.

The equalizing process can also be noticed in Figure 6. Here the color of the cells goes from orange (80% humidity) back to yellow (100%) in the beginning of the drying season and then from green (60%) back to orange between days 60 and 100. Since no solar radiation is present during the night-time, the material stays in the Drying container and does not go through the dryer, therefore the humidity in the cells start to influence one another, meaning that the cells with less water content will absorb some from the cells with more water.

In Figure 7 it is possible to note that when the material is below the threshold humidity of 49% it is then transported to the Store container. By the end of the 150 days all material is transported to the Store container using the parameter defined above. Here, all the cells are represented in blue because of their similar humidity (around 40%-60%). Nevertheless, since each cell enter the container with a respective water content, the equalization process also takes place in this container.

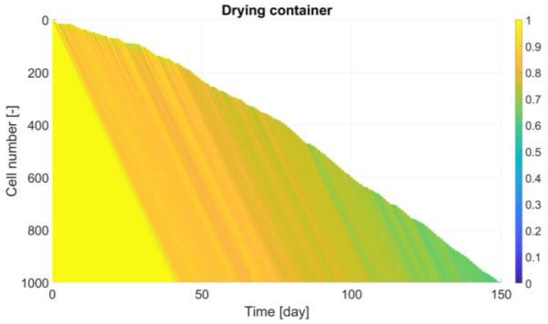

Figure 6: Humidity in the Drying container with 1000 cells and average weather

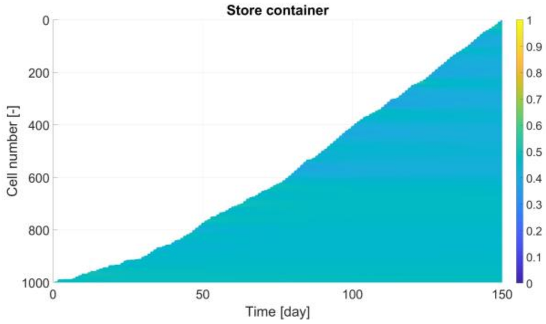

Figure 7: Humidity in the Store container with 1000 cells and average weather

Aiming to understand how the system behaves in different years, several varying weather data sets were used. In a real system, the solar generator and dryer operation hast to be sufficient to reach the storage requirements. In the simulation model that step corresponds to varying Heat transfer factors. In a given system, the threshold of humidity inside of the Store container can be raised or lowered, allowing different grades of humid material to be stored. Both operations can be implemented or just one of them, depending on the desired result.

Figure 8 and Figure 9 present the results using the following input parameters:

- Humidity leveling factor (hf): 0.4
- Divider threshold: 47%
- Number of cells in container: 1000
- Time: 150 days
- Extreme (warm) summer weather data

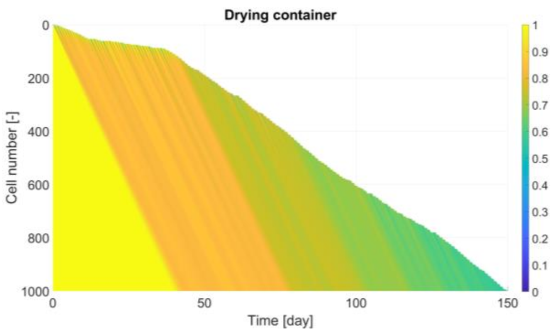

Figure 8: Humidity in the Drying container with 1000 cells and extreme summer weather

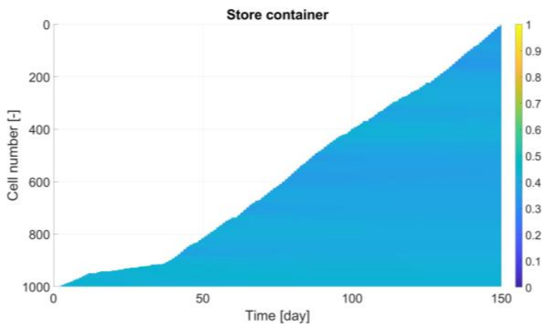

Figure 9: Humidity in the Store container with 1000 cells and extreme summer weather

Figure 8 presents similar behavior observed in Figure 6, but due to a weather data set that represents a hot summer, the divider threshold was set to 47%. Here the equalization also takes place during the night- time and it is also possible to observe the change in the colors of the cells from yellow (100% water content) till green (60%) by the end of the season in the humid material container. The reason why the threshold of the divider is changed in this case is because the days of the extreme summer weather data present a higher irradiation value when compared to the average year weather data.

Figure 9 presents the humidity of the cells that were transported to the Store tank. It is possible to notice that in this case the material transported to the Store container presents darker shades of blue when compared to the material dried with an average year data. This means that during the year with a hot summer, the material will present lower water content as in a year with average irradiance values.

The following results were obtained by using a cool weather regime data. In this case the divider threshold had to be increased to 0.54 in order to have all the material in the Store tank by the end of the drying season. The following parameters were implemented:

- Humidity leveling factor (hf): 0.4
- Divider threshold: 54%
- Number of cells in container: 1000
- Time: 150 days
- Extreme cold weather data

As in the previous results, Figure 10 present how the cells behave inside of the Drying container before they reach the threshold and are moved to the Store container. In this case it is possible to notice that the orange area representing a humidity between 80 and 90% is larger in comparison with the other results. This means that due to the lower irradiance in this period, the material takes a longer time to be dried. Moreover, since the material that goes to the dryer returns to the Drying container with a water content minimally different from the one it had before the drying process, the equalization of the humidity needs a longer time to be observed.

In Figure 11 the equalization process can also be observed. It is possible to notice that the cells in the Dried container have a lighter shade of blue, which means that the water content lies in between 40 and 60%. In comparison, to the other results, in this case, the material presents the highest humidity by the end of the drying season.

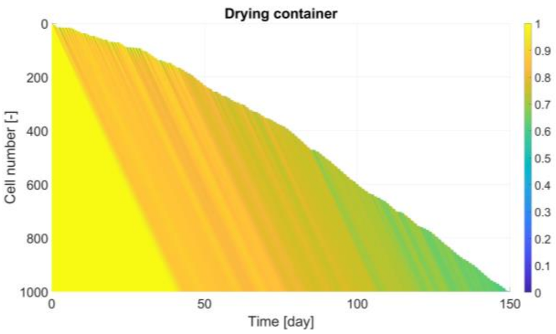

Figure 10: Humidity in the Drying container with 1000 cells and extreme cold weather

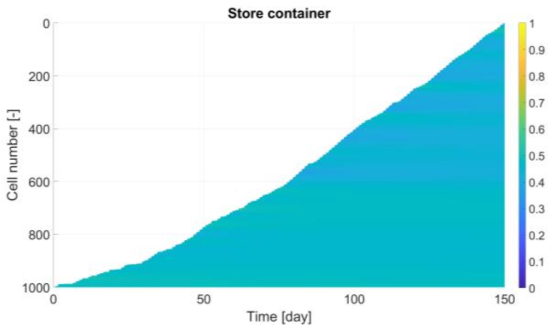

Figure 11: Humidity in the Store container with 1000 cells and extreme cold weather

3.3. Further work

Sorption model

As further steps of this work, an adsorption model will be implemented in the dryer to simulate how the zeolite will be dried based on the performance of a PV generator and the process parameters (temperature and ambient humidity) of a desorption reactor.

The numerical model to be used in this work represents an open sorption storage system with a fixed zeolite bed. An axial humid airflow drives the sorption process and allows direct charging/discharging of the sorption material. The model implementation was previously done in Simulink, an additional package of MATLAB by (Daborer-

Prado, et al. 2020). In order to perform the numerical simulations, the model is based on the following assumptions:

- The model assumes a one-dimensional approach, where no radial influence is considered
- A homogeneous model for storage material and air flow is used, i.e., it is assumed that the air leaves each store node with the node temperature TS(i), where (i) represents the node number
- The specific heat capacities of the solid and air are not function of the humidity or of the temperature in the system
- The sorption equilibrium is modelled by the Dubinin-Astakhov-approach and the reaction kinetics is described by a linear driving force ansatz.
- The specific heat capacity of the air is not a function of the humidity or of the temperature in the system; the specific heat capacity of the solid is only a function of humidity (water loading) but not of the temperature in the system.

Photovoltaic generator

The PV generator block to be used in combination with the sorption model of this project, calculates the DC output of a PV module in W based on the module characteristic parameters (Juelich 2020):

- Pmax: Peak power (Wp) of one module at Standard Test Conditions (STC) [W]
- Dirt and degradation effects
- ΔWp: Temperature coefficient of power drop of Pmax [1/K]

The following equation is used as base for the model calculation of power:

$$P = \frac{Solar\ radiation}{1000} * Incidence\ angle\ modifier * P_{max} * (1 - \left(T_{amb} + 40 * \frac{Solar\ Power}{1000}\right) - 25°C)$$

The incidence angle modifier is 1 for vertical direct solar radiation and the model follows the Fresnel law. The subsequent assumptions were made for the temperature model of the module:

- The module presents 25°C at STC
- 40 K temperature difference to ambient at full solar radiation (1000 W/m²)

Besides the characteristic parameters, the main inputs of the model are a weather data set and the position (azimuth and inclination) of the module.

4. Conclusions

As previously stated, in the past years, with the increase in use of renewable energy sources, the need for new methods of storage solutions is more important than ever. Special attention should be given to systems able to store the large supply of solar energy available during summer and applying it during winter, when the accessible quantity of energy is lower. In this study a seasonal storage system model was developed that should fulfill the aim of having a high energy density and low thermal losses.

In summary, this work presented the creation of two containers (Store and Drying) used to storage the dried and the humid material, respectively. A model for a dryer based on different types of weather data was presented, moreover, the operation principle for the divider was also developed. The results show how the weather data used can influence the system. By using the extreme weather data, the material in the Store container presents the lowest water content by the end of the drying season varying between 30 and 40%. On the other hand, with the extreme winter data, the material has the highest water content values (40-55%).

Further steps of this work are the inclusion of an adsorption model that takes into account the temperature of the ambient and inlet air as well as the material proprieties of the zeolite. Moreover, a PV generator will also be included in the next steps of this project. The generator will be used to power the adsorption system to be included in the dryer system.

5. Acknowledgments

This work is financed by research subsidies granted by the government of Upper Austria and the research project “SorSens- Development of a virtual sensor for State-of-charge determination of sorption heat storage” which is financially supported by the Austrian Climate and Energy Fund (KLIEN) and the Austrian Research Fund (FFG-grant number 881187).

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